Opportunities of light ion collisions at the LHC

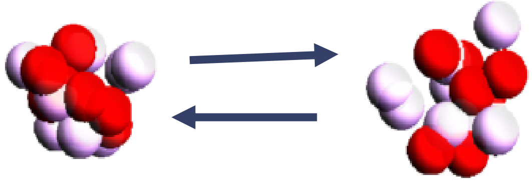
Towards smaller and smaller QGPs

Based on workshop OppOrtunities at the LHC, with Jasmine Brewer and Aleksas Mazeliauskas (2103.01939)

Parton energy loss based on (2007.13754 (PRL) and 2007.13758 (PRC))
with Alexander Huss, Aleksi Kurkela, Aleksas Mazeliauskas, Risto Paatelainen and Urs Wiedemann

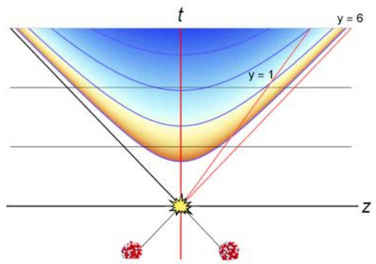
pp reference estimates, with Jasmine Brewer, Alexander Huss and Aleksas Mazeliauskas (2108.13434)

Trajectum results to appear with Govert Nijs



Wilke van der Schee
Snowmass, Boston
2 September 2021

Ridges everywhere: *panta rei*

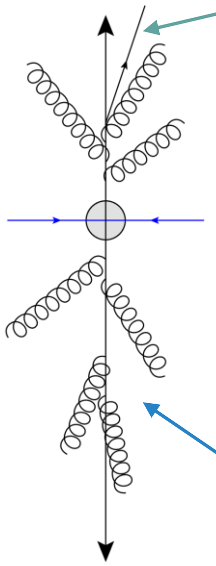


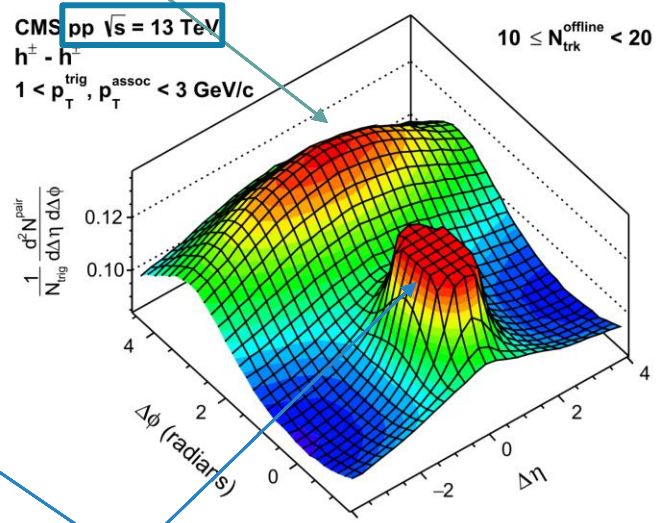
1. Ridge at Δϕ=0 and **large Δη**: *an initial or geometric effect*

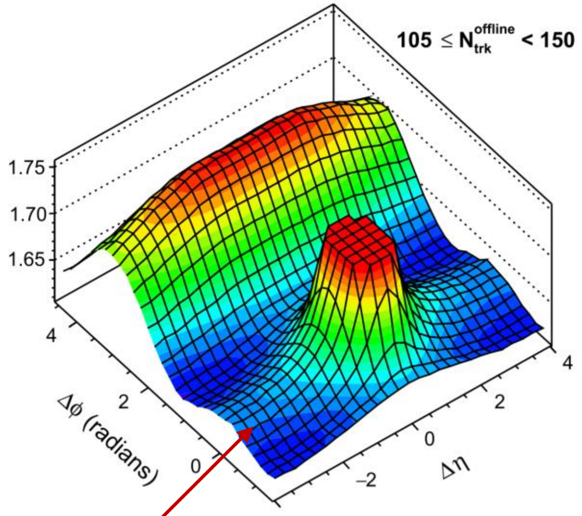
Back-to-back jet

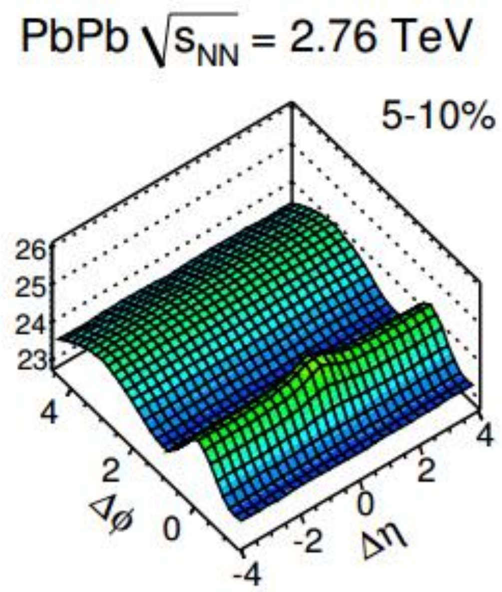
Low multiplicity

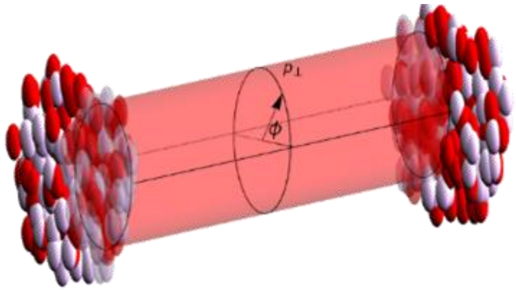
High multiplicity







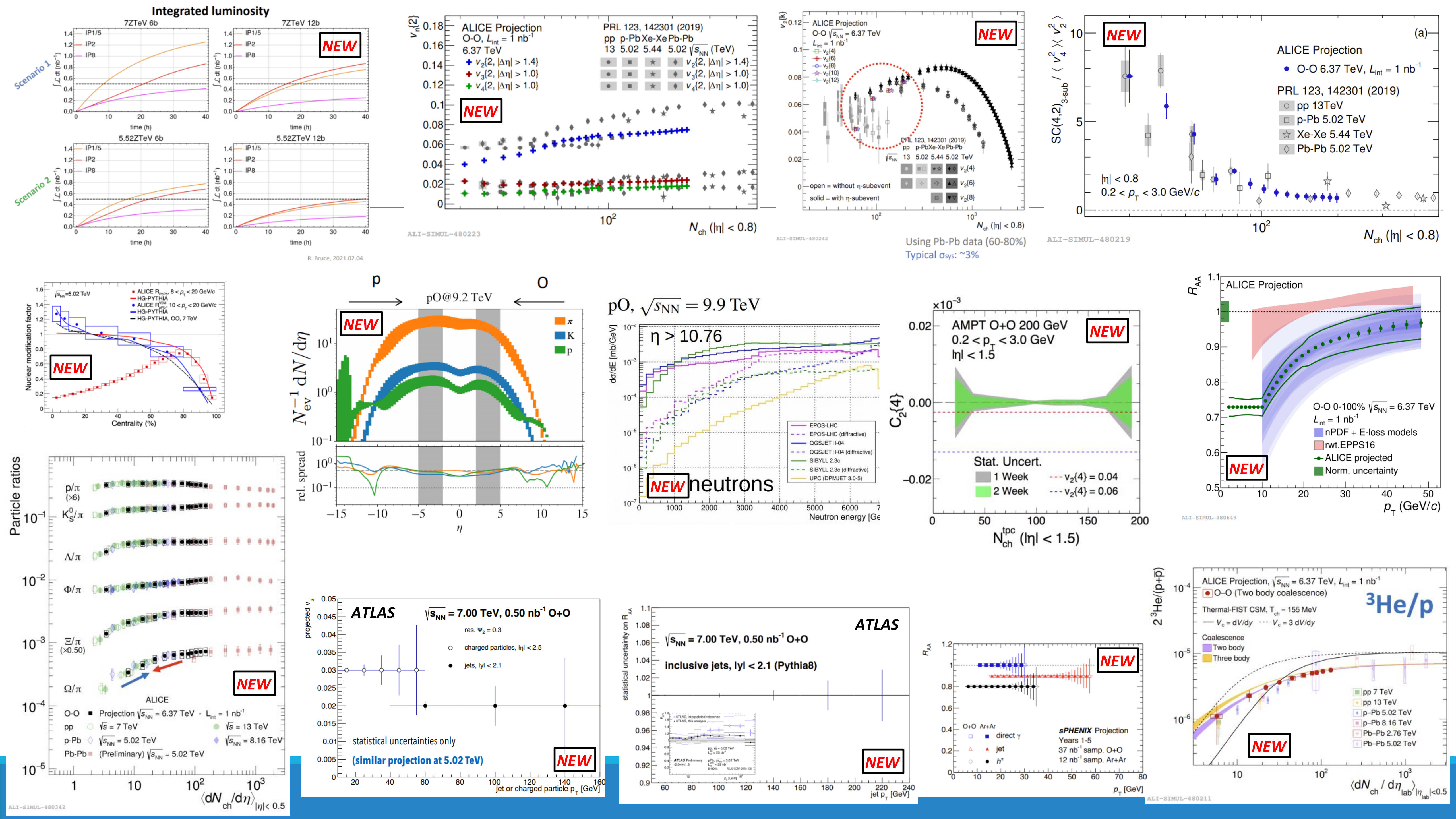




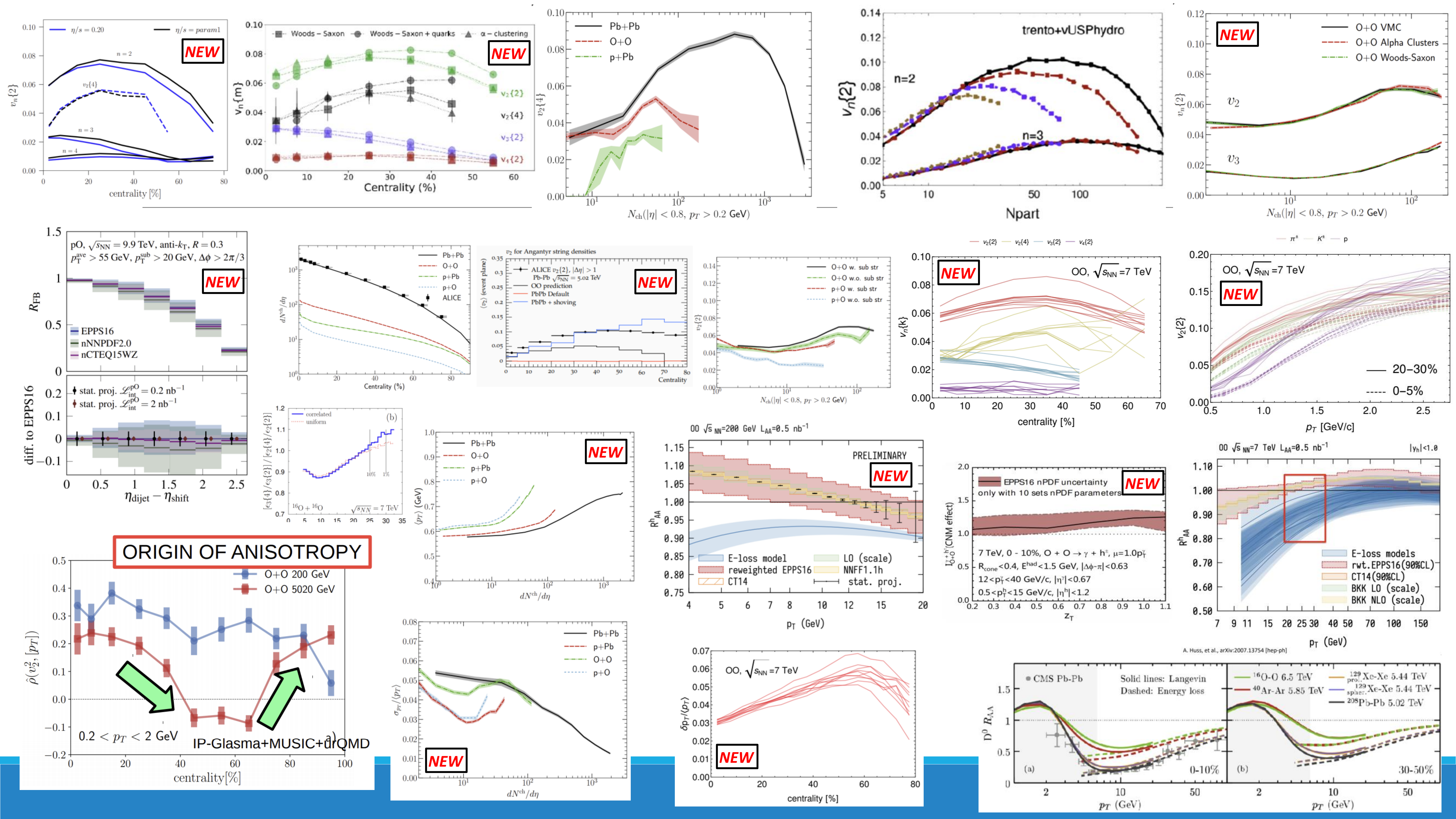
Jet fragmentation

(nearside)**Ridge**

CMS, Evidence for collectivity in pp collisions at the LHC (2016)



Integrated luminosity
7ZTeV 6b
7ZTeV 12b
5.52ZTeV 6b
5.52ZTeV 12b
Scenario 1
Scenario 2
IP1/5
IP2
IP8
time (h)
R. Bruce, 2021.02.04
NEW
ALICE Projection
O-O, L_{int} = 1 nb^{-1}
6.37 TeV
$v_2\{2, |\Delta\eta| > 1.4\}$
$v_3\{2, |\Delta\eta| > 1.0\}$
$v_4\{2, |\Delta\eta| > 1.0\}$
PRL 123, 142301 (2019)
pp p-Pb Xe-Xe Pb-Pb
13 5.02 5.44 5.02 $\sqrt{s_{NN}}$ (TeV)
N_{ch} ($|\eta|$ < 0.8)
ALI-SIMUL-480223
ALICE Projection
O-O $\sqrt{s_{NN}}$ = 6.37 TeV
L_{int} = 1 nb^{-1}
open = without η-subevent
solid = with η-subevent
ALI-SIMUL-480242
Using Pb-Pb data (60-80%)
Typical σsys: ~3%
ALICE Projection
O-O 6.37 TeV, L_{int} = 1 nb^{-1}
PRL 123, 142301 (2019)
pp 13TeV
p-Pb 5.02 TeV
Xe-Xe 5.44 TeV
Pb-Pb 5.02 TeV
$|\eta|$ < 0.8
0.2 < p_T < 3.0 GeV/c
$SC(4,2)_{3\text{-sub}} / \langle v_4^2 \rangle \langle v_2^2 \rangle$
ALI-SIMUL-480219
Nuclear modification factor
$\sqrt{s_{NN}}$=5.02 TeV
ALICE R_{PbPb}, 8 < p_T < 20 GeV/c
HG-PYTHIA
ALICE R_{pPb}^{V0M}, 10 < p_T < 20 GeV/c
HG-PYTHIA
HG-PYTHIA, OO, 7 TeV
Centrality (%)
p
O
pO@9.2 TeV
$N_{ev}^{-1}\, dN/d\eta$
rel. spread
π
K
p
η
pO, $\sqrt{s_{NN}}$ = 9.9 TeV
η > 10.76
neutrons
dσ/dE [mb/GeV]
EPOS-LHC
EPOS-LHC (diffractive)
QGSJET II-04
QGSJET II-04 (diffractive)
SIBYLL 2.3c
SIBYLL 2.3c (diffractive)
UPC (DPMJET 3.0-5)
Neutron energy [GeV]
AMPT O+O 200 GeV
0.2 < p_T < 3.0 GeV
$|\eta|$ < 1.5
$C_2\{4\}$
Stat. Uncert.
1 Week
2 Week
$v_2\{4\}$ = 0.04
$v_2\{4\}$ = 0.06
N_{ch}^{tpc} ($|\eta|$ < 1.5)
ALICE Projection
O-O 0-100% $\sqrt{s_{NN}}$ = 6.37 TeV
L_{int} = 1 nb^{-1}
nPDF + E-loss models
rwt.EPPS16
ALICE projected
Norm. uncertainty
R_{AA}
p_T (GeV/c)
ALI-SIMUL-480649
Particle ratios
p/π (×6)
K^0_S/π
Λ/π
Φ/π
Ξ/π (×0.50)
Ω/π
ALICE
O-O Projection $\sqrt{s_{NN}}$ = 6.37 TeV - L_{int} = 1 nb^{-1}
pp $\sqrt{s}$ = 7 TeV $\sqrt{s}$ = 13 TeV
p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV $\sqrt{s_{NN}}$ = 8.16 TeV
Pb-Pb (Preliminary) $\sqrt{s_{NN}}$ = 5.02 TeV
$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$
ALI-SIMUL-480342
ATLAS
$\sqrt{s_{NN}}$ = 7.00 TeV, 0.50 nb^{-1} O+O
res. Ψ_2 = 0.3
charged particles, $|\eta|$ < 2.5
jets, $|y|$ < 2.1
projected v_2
statistical uncertainties only
(similar projection at 5.02 TeV)
jet or charged particle p_T [GeV]
ATLAS
$\sqrt{s_{NN}}$ = 7.00 TeV, 0.50 nb^{-1} O+O
inclusive jets, $|y|$ < 2.1 (Pythia8)
statistical uncertainty on R_{AA}
jet p_T [GeV]
R_{AA}
O+O Ar+Ar
direct γ
jet
$h^{\pm}$
sPHENIX Projection
Years 1-5
37 nb^{-1} samp. O+O
12 nb^{-1} samp. Ar+Ar
p_T [GeV]
ALICE Projection, $\sqrt{s_{NN}}$ = 6.37 TeV, L_{int} = 1 nb^{-1}
O–O (Two body coalescence)
^{3}He/p
Thermal-FIST CSM, T_{ch} = 155 MeV
V_c = dV/dy
V_c = 3 dV/dy
Coalescence
Two body
Three body
pp 7 TeV
pp 13 TeV
p–Pb 5.02 TeV
p–Pb 8.16 TeV
Pb–Pb 2.76 TeV
Pb–Pb 5.02 TeV
2 ^{3}He/(p+$\bar{p}$)
$\langle dN_{ch}/d\eta_{lab} \rangle_{|\eta_{lab}|<0.5}$
ALI-SIMUL-480211



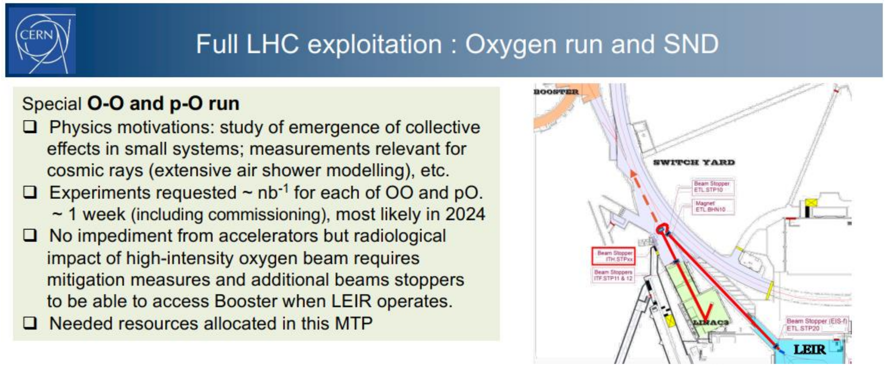
ORIGIN OF ANISOTROPY
NEW
η/s = 0.20
η/s = param1
centrality [%]
Woods – Saxon
Woods – Saxon + quarks
α – clustering
Centrality (%)
v2{2}
v2{4}
v3{2}
v4{2}
Pb+Pb
O+O
p+Pb
Nch(|η| < 0.8, pT > 0.2 GeV)
trento+vUSPhydro
n=2
n=3
Npart
O+O VMC
O+O Alpha Clusters
O+O Woods-Saxon
pO, √sNN = 9.9 TeV, anti-kT, R = 0.3
EPPS16
nNNPDF2.0
nCTEQ15WZ
diff. to EPPS16
ηdijet − ηshift
p+O
ALICE
Centrality (%)
v2 for Angantyr string densities
ALICE v2{2}, |Δη| > 1
Pb-Pb √sNN = 5.02 TeV
OO prediction
PbPb Default
PbPb + shoving
O+O w. sub str
O+O w.o. sub str
p+O w. sub str
p+O w.o. sub str
OO, √sNN =7 TeV
centrality [%]
20–30%
0–5%
pT [GeV/c]
correlated
uniform
16O + 16O
√sNN = 7 TeV
dNch/dη
OO √sNN=200 GeV LAA=0.5 nb−1
PRELIMINARY
E-loss model
reweighted EPPS16
CT14
LO (scale)
NNFF1.1h
stat. proj.
pT (GeV)
EPPS16 nPDF uncertainty
only with 10 sets nPDF parameters
7 TeV, 0 - 10%, O + O → γ + h±, μ=1.0pTγ
zT
OO √sNN=7 TeV LAA=0.5 nb−1
E-loss models
rwt.EPPS16(90%CL)
CT14(90%CL)
BKK LO (scale)
BKK NLO (scale)
O+O 200 GeV
O+O 5020 GeV
0.2 < pT < 2 GeV
IP-Glasma+MUSIC+urQMD
A. Huss, et al., arXiv:2007.13754 [hep-ph]
CMS Pb-Pb
Solid lines: Langevin
Dashed: Energy loss
16O-O 6.5 TeV
40Ar-Ar 5.85 TeV
129Xe-Xe 5.44 TeV
208Pb-Pb 5.02 TeV
0-10%
30-50%

OppOrtunities at the LHC

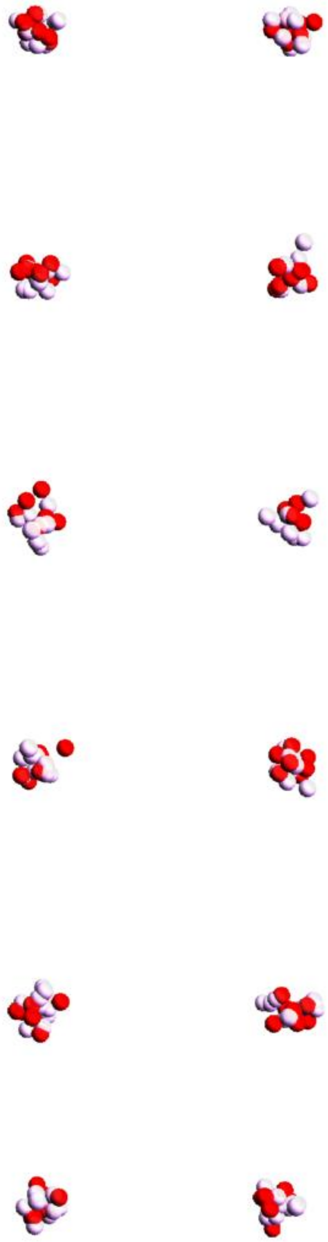
1. Workshop was a success
   - On average 186 unique participants per day over 5 days
   - Many new computations and projections

2. One crucial discussion point: the colliding energy
   - Maximum magnetic field: around 7 TeV
   - But perhaps no *pp* reference available? It is however difficult to lower the energy

June CERN council:
Potential OO pilot run → Special run
Full LHC exploitation


Full LHC exploitation : Oxygen run and SND

Special **O-O and p-O run**
- Physics motivations: study of emergence of collective effects in small systems; measurements relevant for cosmic rays (extensive air shower modelling), etc.
- Experiments requested ~ nb^{-1} for each of OO and pO. ~ 1 week (including commissioning), most likely in 2024
- No impediment from accelerators but radiological impact of high-intensity oxygen beam requires mitigation measures and additional beams stoppers to be able to access Booster when LEIR operates.
- Needed resources allocated in this MTP

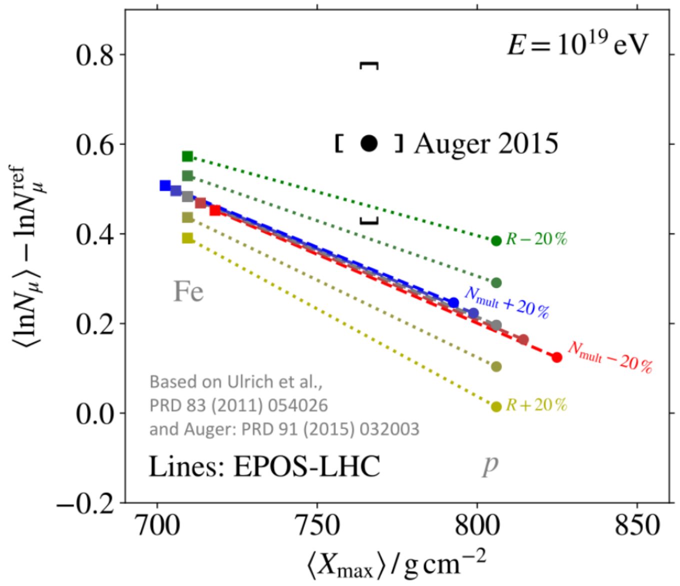


A brief cosmic-ray perspective

Muon puzzle in cosmic air showers

- Cascade of energetic collisions, producing muons and photons
- Difficult to *simultaneously* predict
  - Number of muons
  - Depth of air shower (in air density units)

- Relies crucially on ratio π_0: $R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$



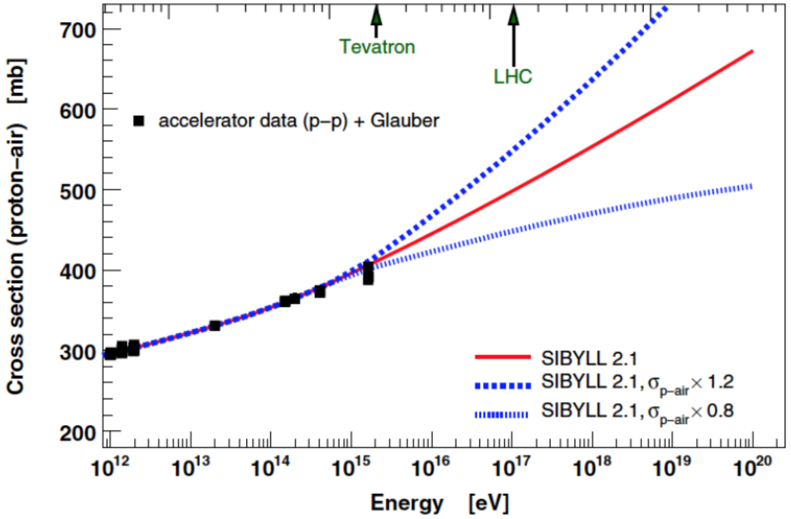
Ralf Ulrich, Ralph Engel and Michael Unger, Hadronic multiparticle production at ultrahigh energies and extensive air showers (2011)
Hans Dembinski, Oxygen beams and LHCb: prospects of pO and OO collisions for nuclear and astroparticle physics: cern.ch/oppoatlhc/contributions/4172211/

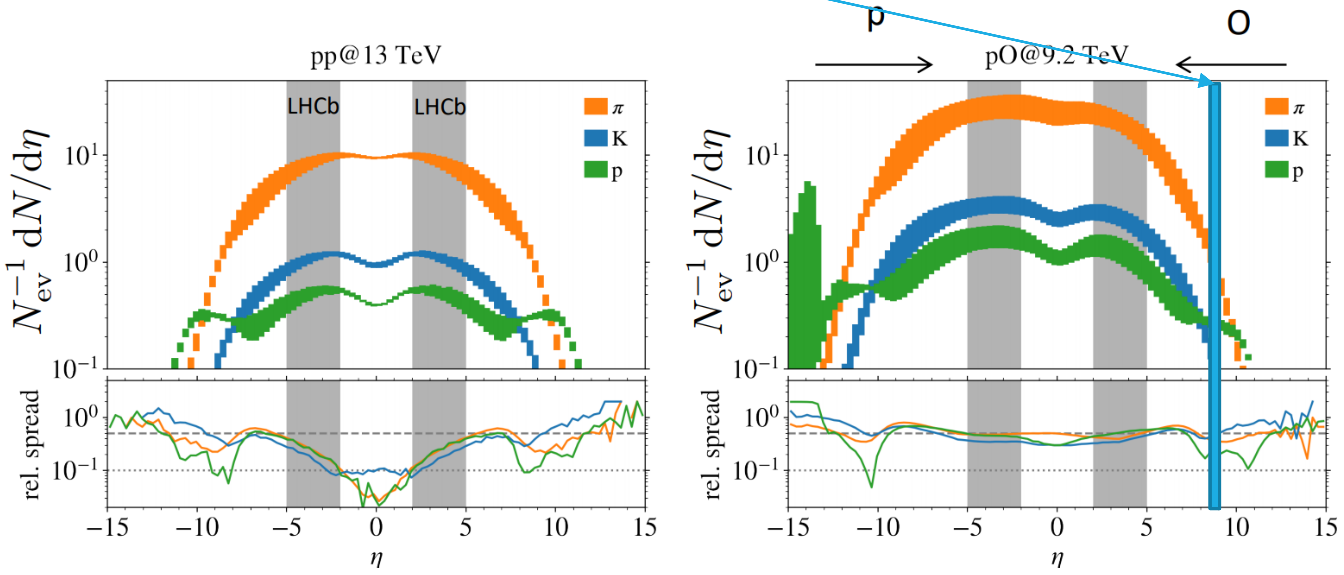
A brief cosmic-ray perspective

LHC contribution

- Proton-oxygen cross section: large uncertainty
- Spectrum at very forward rapidities
- Help with π_0 ratio? Strangeness? QGP?

LHCf: this is were most of the energy is deposited (ends after run 3)





Strangeness: from pQCD to thermal

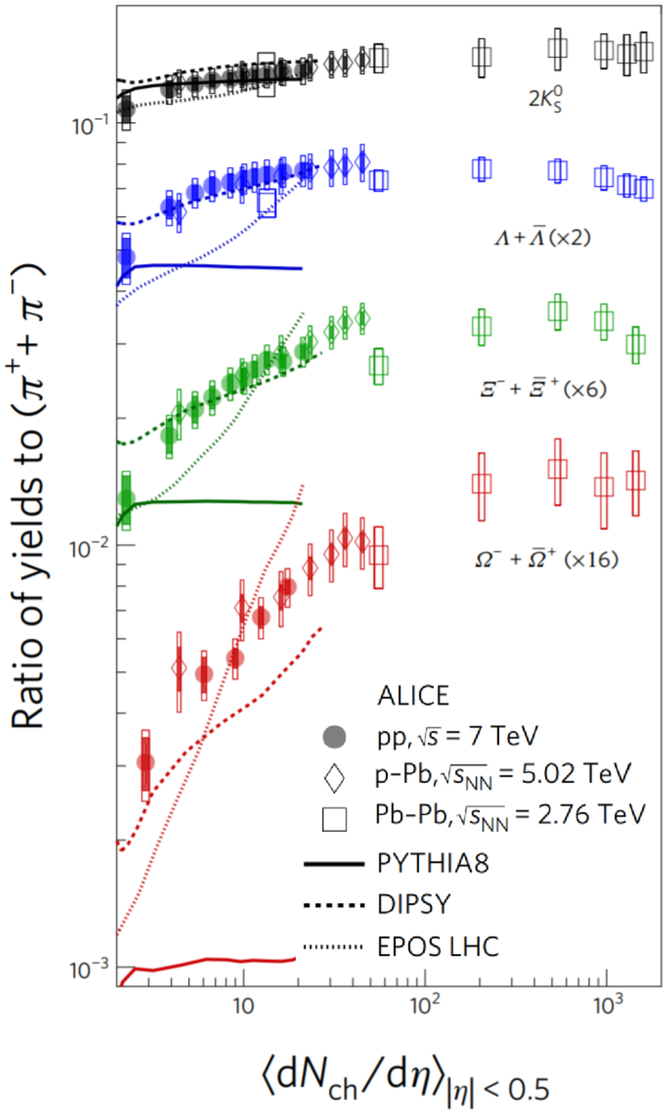
1. Ratio of strange baryons versus pions
    - Pythia fits low multiplicity
        - But constant towards higher multiplicity (!)

Thermodynamical string fragmentation

Nadine Fischer[a,b] and Torbjörn Sjöstrand[a] *January 31, 2017*

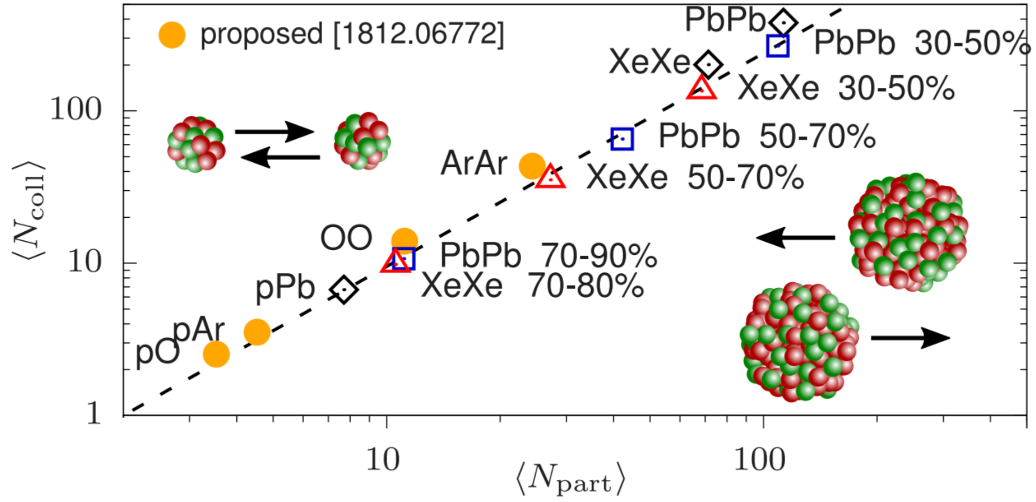
ABSTRACT: The observation of heavy-ion-like behaviour in pp collisions at the LHC suggests that more physics mechanisms are at play than traditionally assumed.

2. Saturates for high multiplicity pPb / PbPb
    - Interpretation: thermal strangeness production

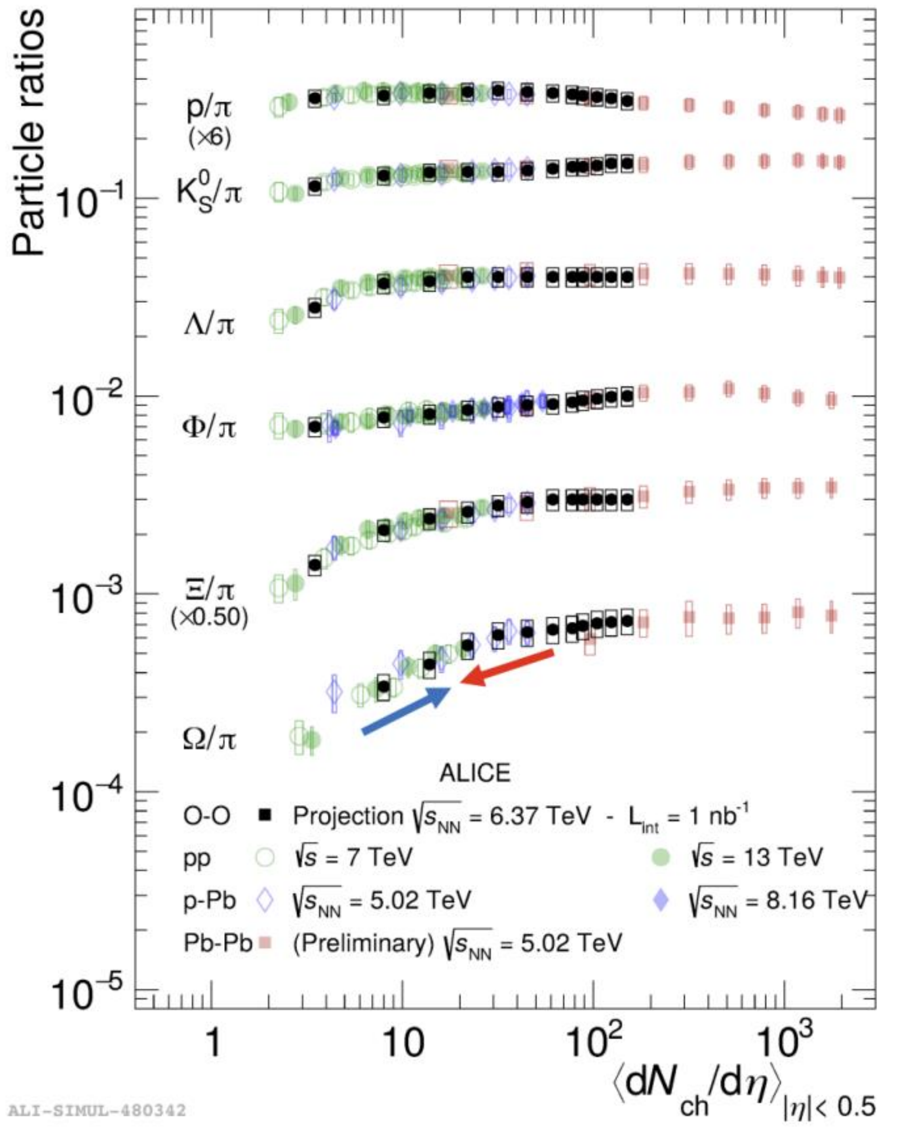


Strangeness: OO fills the gap

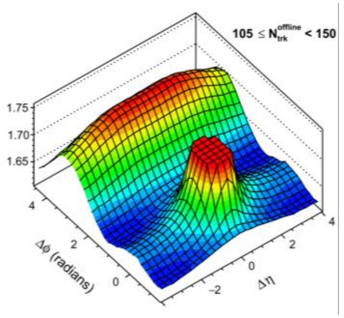
1. Oxygen collisions would provide unique opportunity to smoothly connect pPb and PbPb



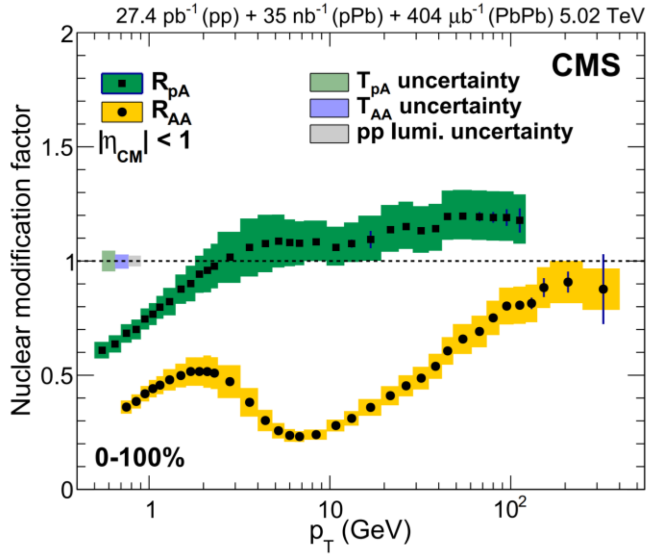
2. Caveat: large statistics pPb and PbPb could extend curves
   - But at the price of selecting 'atypical' events



A puzzle: flow in *p*Pb or *pp* collisions?



1. There seems to be flow
   - Quite some modeling, but everything consistent with hydro (does not prove hydro!)
2. But: nuclear modification > 1: **no (naive) jet/hadron energy loss**



A simple energy loss model with one free parameter

1. Take minimum bias point at 54 GeV PbPb at 2.76 TeV, and fix d (= $\hat{q}/T^3$)

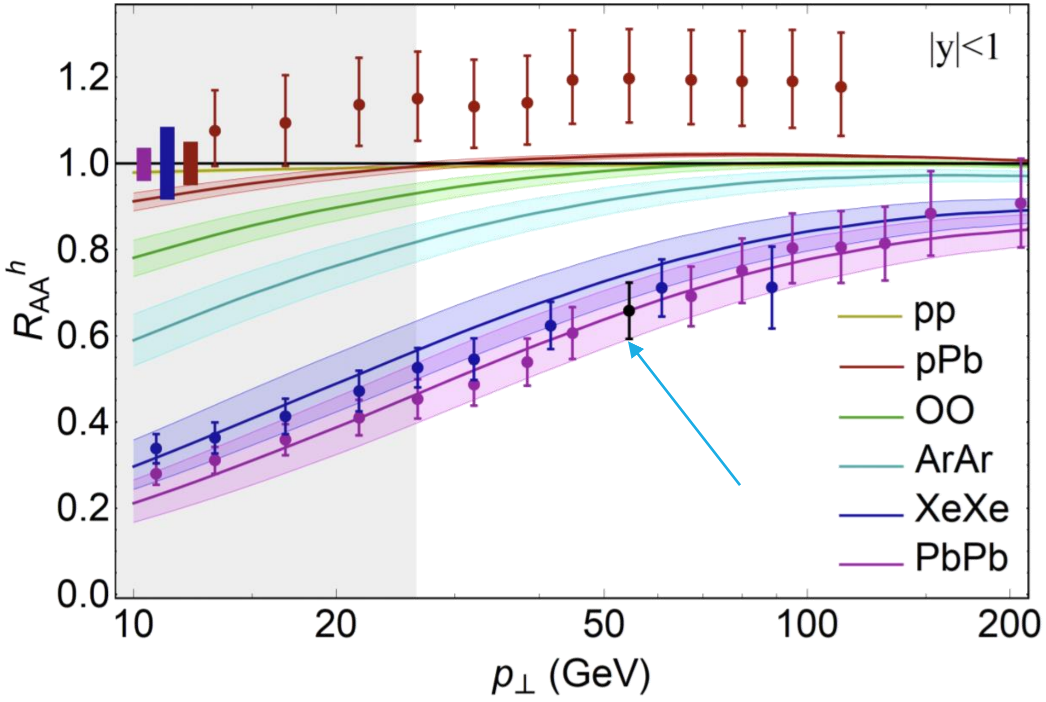
   Note: error only from d

2. Model captures p_T dependence

3. *p*Pb perhaps consistent with T_{AA} error (boxes)

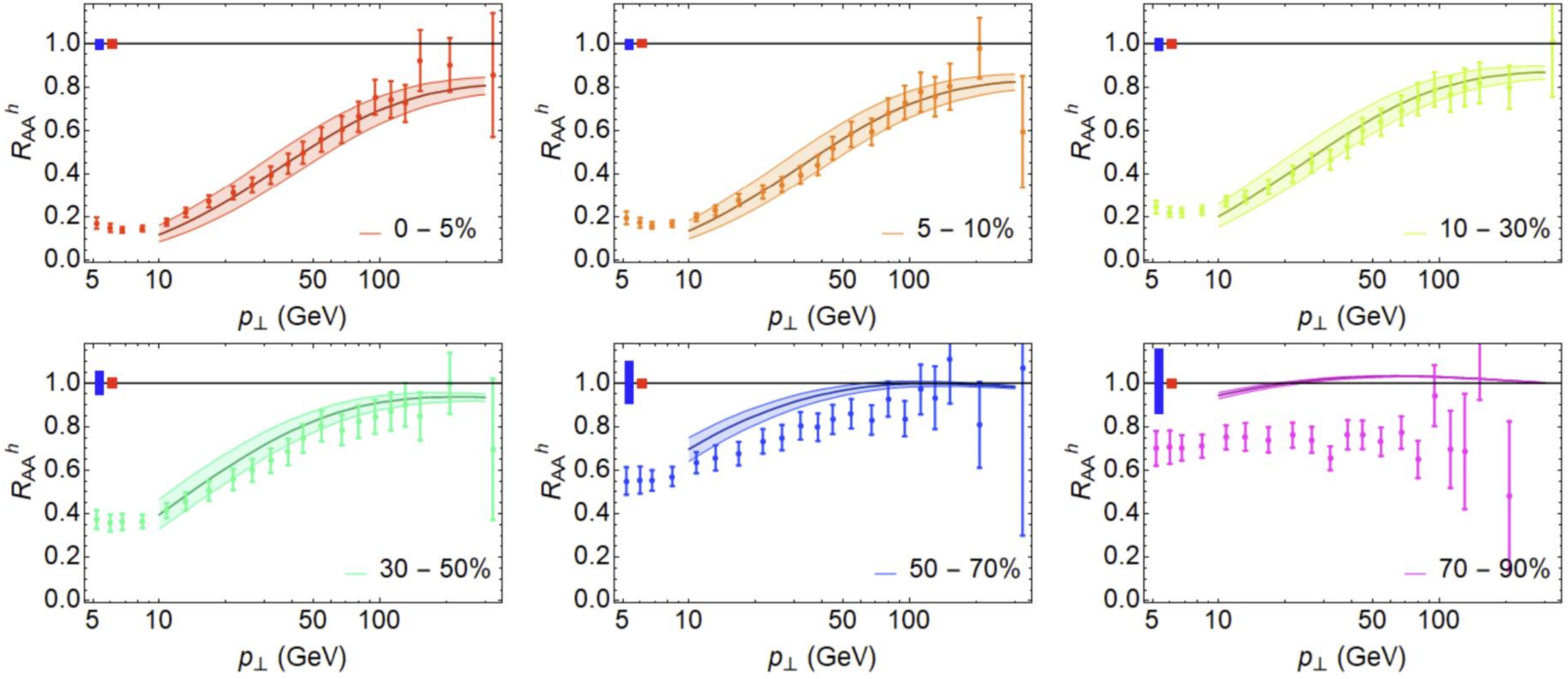
4. Also checked model for pp; almost no modification

5. Energy loss: BDMPS-Z



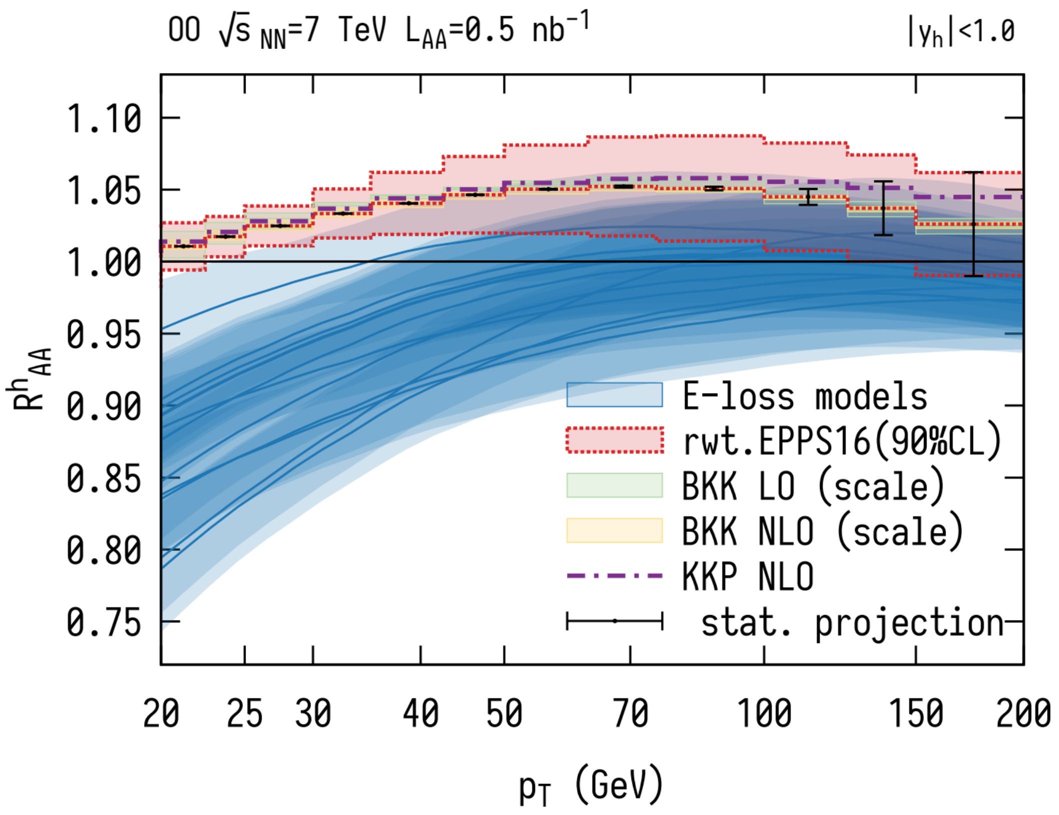
Centrality dependence

1. Captures centrality dependence, except most peripheral bin (though note box = T_{AA} uncertainty)



Extrapolate to OO collisions

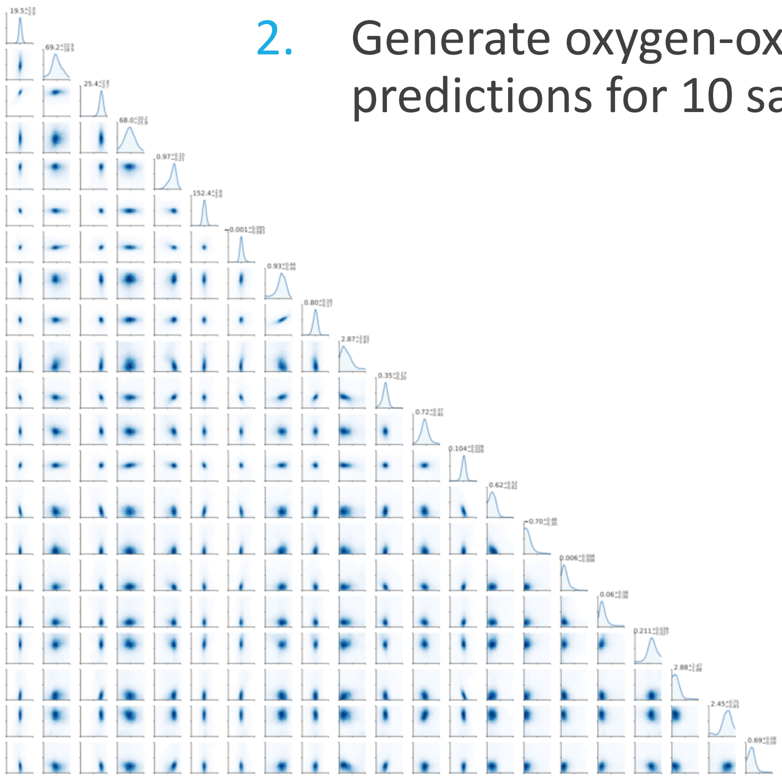
1. Final band of all model predictions to OO:
   - *As agnostic as possible*
   - *Baseline without QGP: including reweighting of nPDF set*

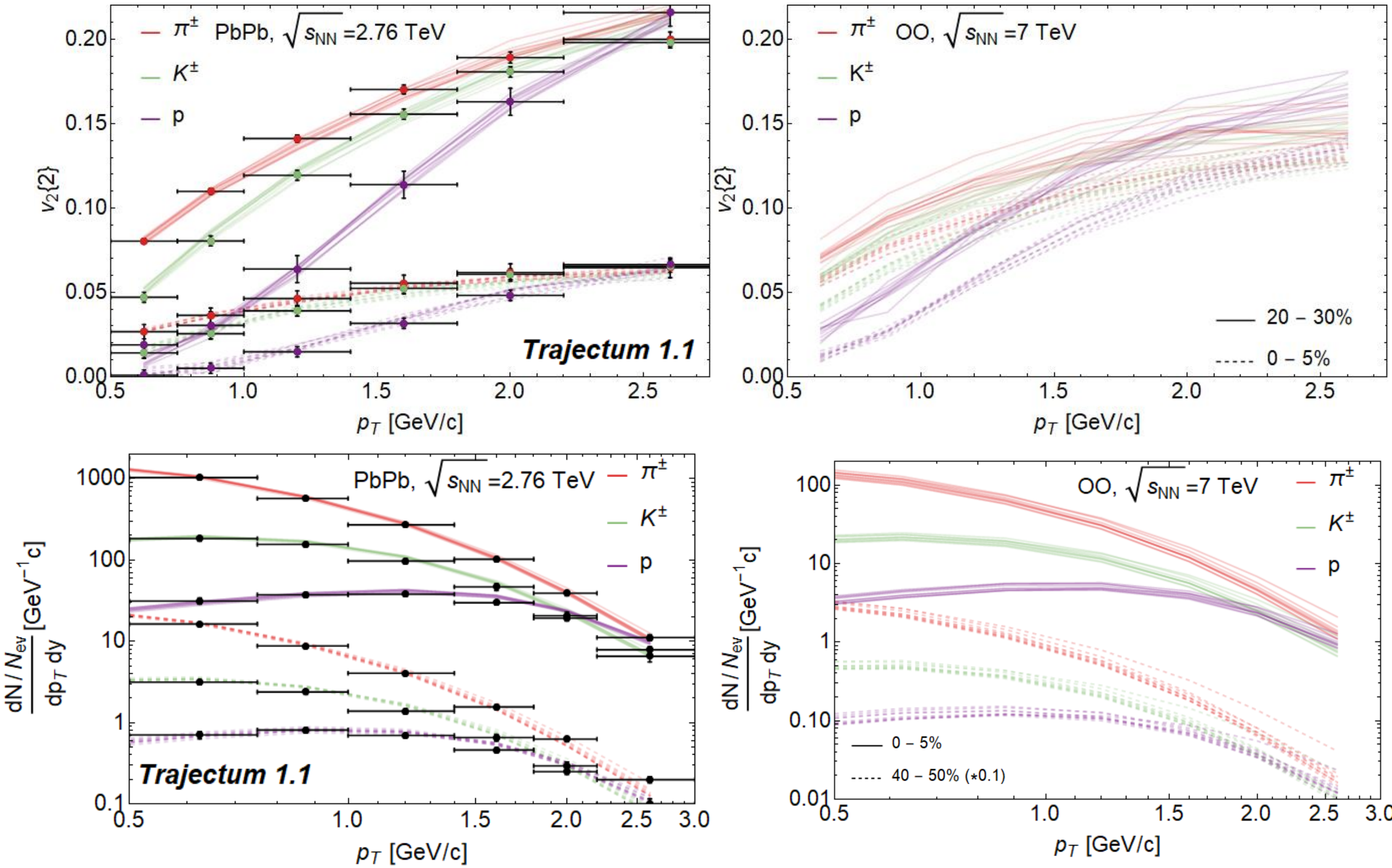


Can oxygen collisions constrain QGP properties?

1. Perform a Bayesian estimate of likelihoods PbPb parameters

2. Generate oxygen-oxygen predictions for 10 samples:

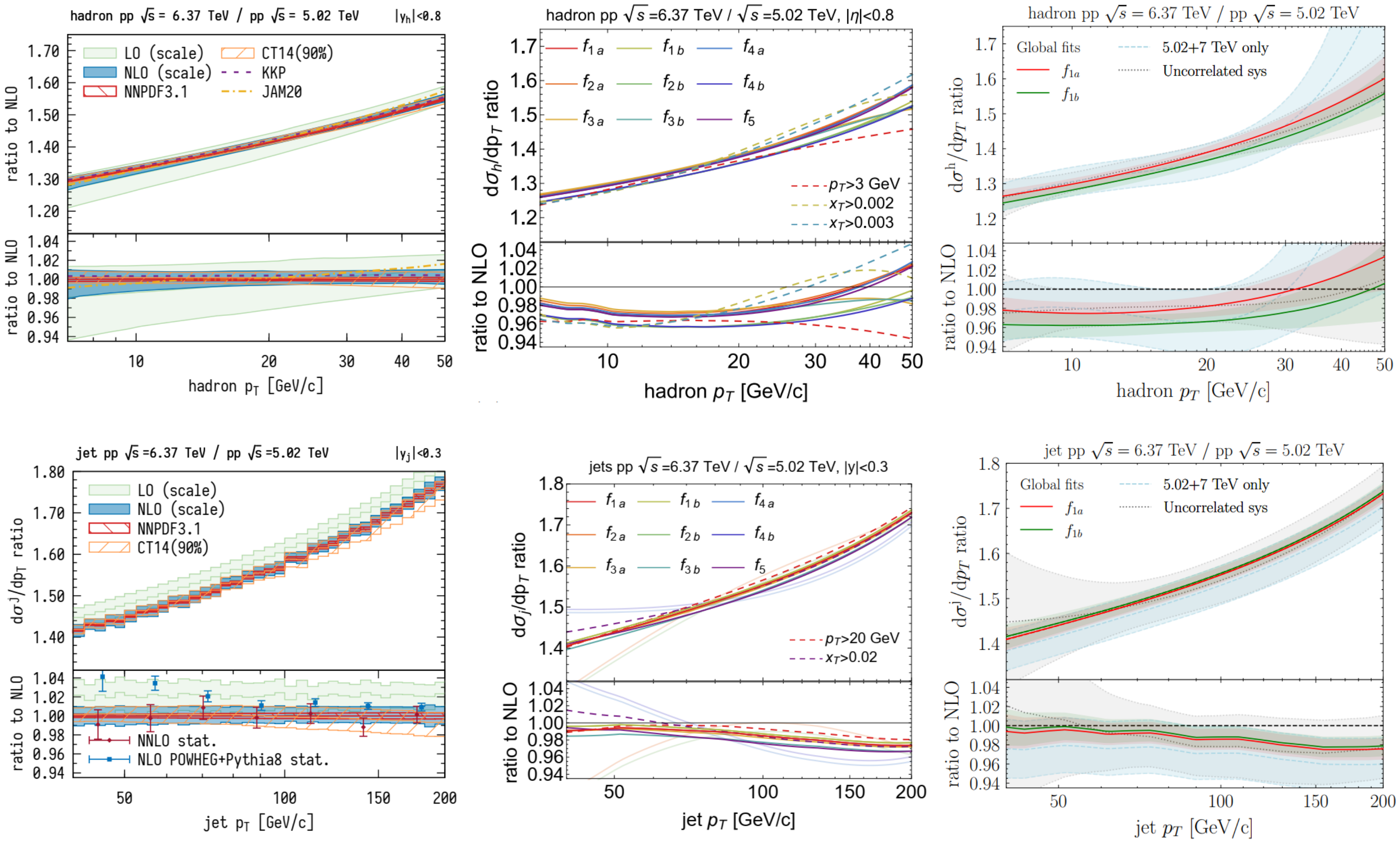




A *pp* reference or no *pp* reference?

Needed: ratio of spectra at 6.37/5 TeV; do uncertainties cancel?

NNLO pQCD | Diverse χ^2 (data) | MCMC (data)



Hard to say, without reference a precision estimate is possible (within ~3%),
but precision in small systems is paramount

Jasmine Brewer, Alexander Huss, Aleksas Mazeliauskas and WS, Ratios of jet and hadron spectra at LHC energies: measuring high-p_T suppression without a *pp* reference (2021)

The LHC as a light ion collider

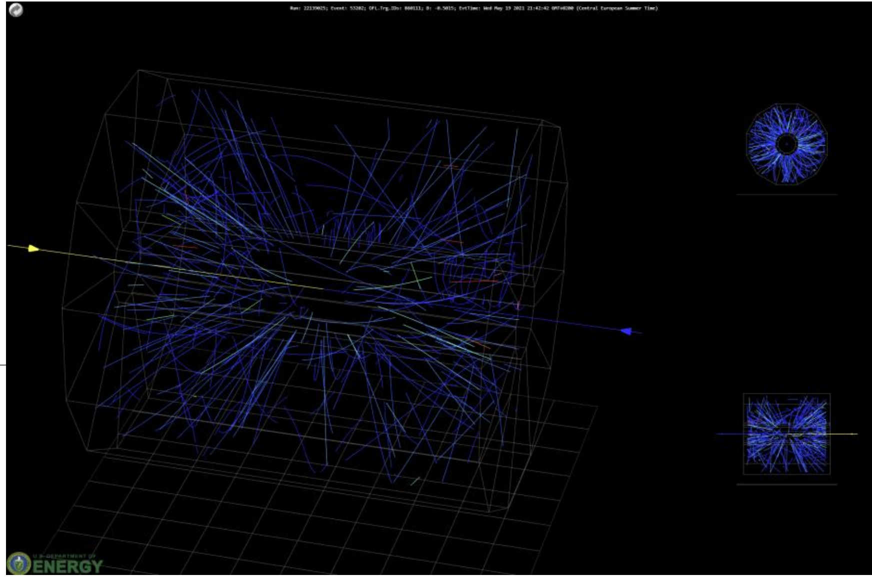
1. Oxygen can provide key to current heavy ion puzzles
   - Is there flow in small systems such as p-Pb collisions?
   - Precision analysis possible on partonic energy loss
     - Theory accurate to few percent in minimum bias collisions
     - Expected effect is larger than precision due to NLO QCD computations including accurate nPDFs
   - Can further constrain QGP properties

2. Proton-oxygen essential for high energy cosmic rays
   - Can also be very helpful to put extra constraints on nPDFs

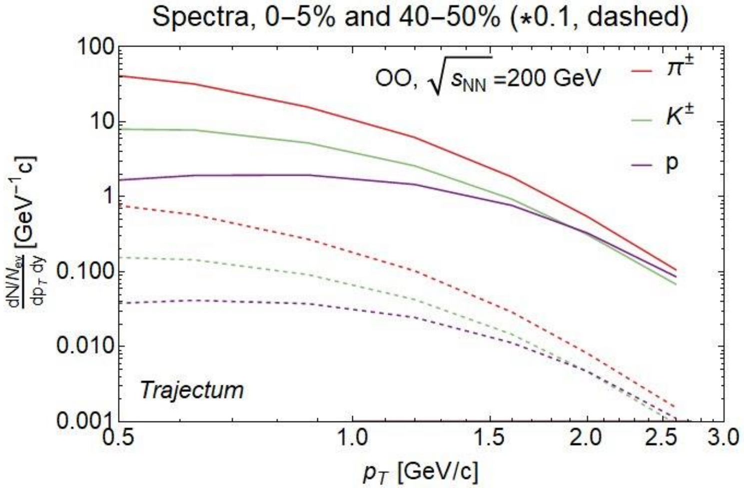
3. Did I skip anything?
   - Structure of oxygen: is oxygen made out of four alpha particles? Seems hard to see significant consequences
   - Impressive projections by ALICE, including anisotropic flow coefficients up to 12-particle cumulants
   - Correlations between mean transverse momentum and anisotropic flow can be interesting
   - Oxygen especially interesting to constrain nPDFs: no data on oxygen so far available even at lower energy

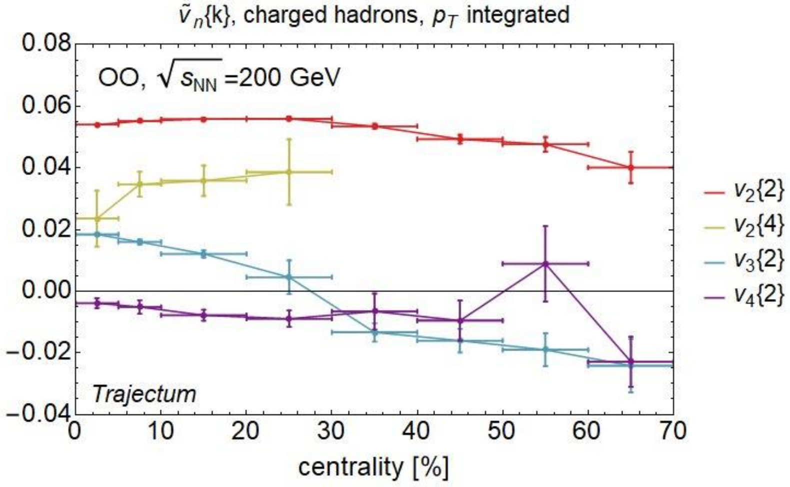
Back-up

Oxygen @ RHIC
Complementary collisions @ 200 GeV

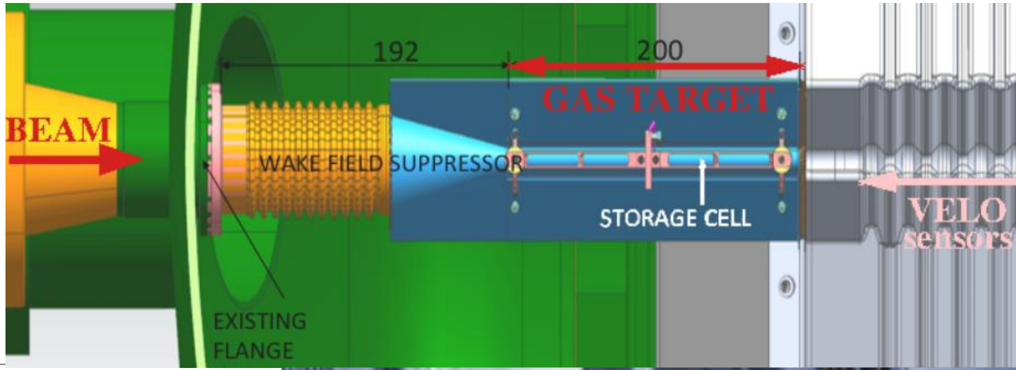


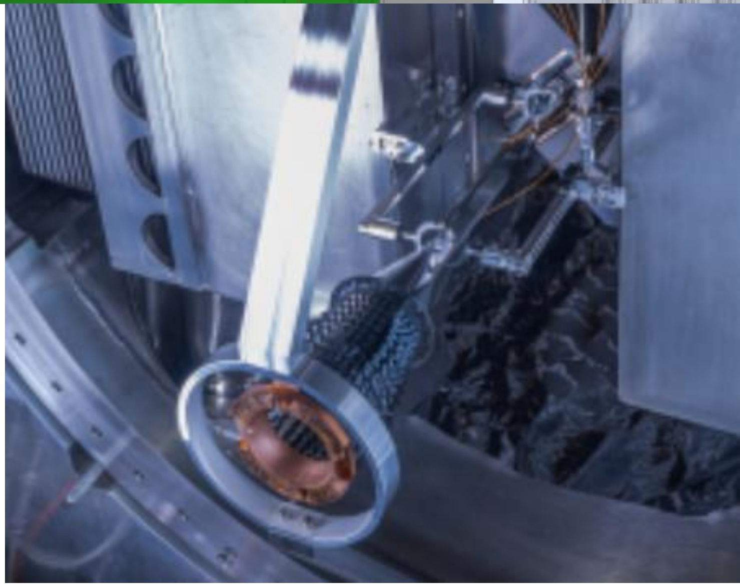
1. (Much) lower multiplicity: more comparable to *p*Pb?
2. Curious signs of anisotropic flow coefficients (typically positive)
3. Exciting time to make predictions:





Light ions and SMOG2
LHCb at fixed target

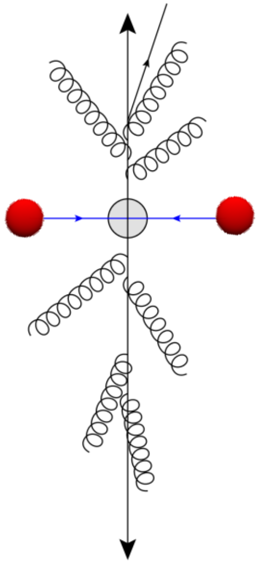




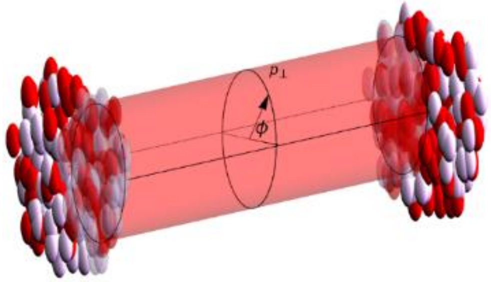
1. Interesting idea: ‘contaminate’ beam with gas (only at LHCb)
2. Fixed target (gas is at rest); options: H, He, N, O, Ar, Ne, Kr, Xe, …
3. Lower energy ($\sqrt{s_{NN}} \simeq 110\,\mathrm{GeV}$): complementary to colliding set-up
4. Possible with *p*, Pb and O in the beam (full year)
5. Data taking simultaneous: sizeable integrated lumi: 100 pb^{-1}

Global analysis perspective: need for a wide variety of colliding systems and energies

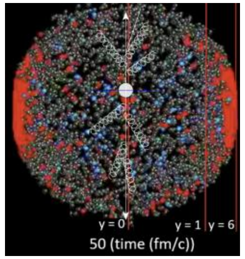
(high energy) ¿HEP versus HIP? (heavy ion)



Low multiplicity	High multiplicity
Jet-like particle shower	Relatively few jets
No equilibration	Equilibration: QGP



Jets important in heavy ion/small systems
Often intermediate multiplicity
QGP-type physics part of *pp* collisions



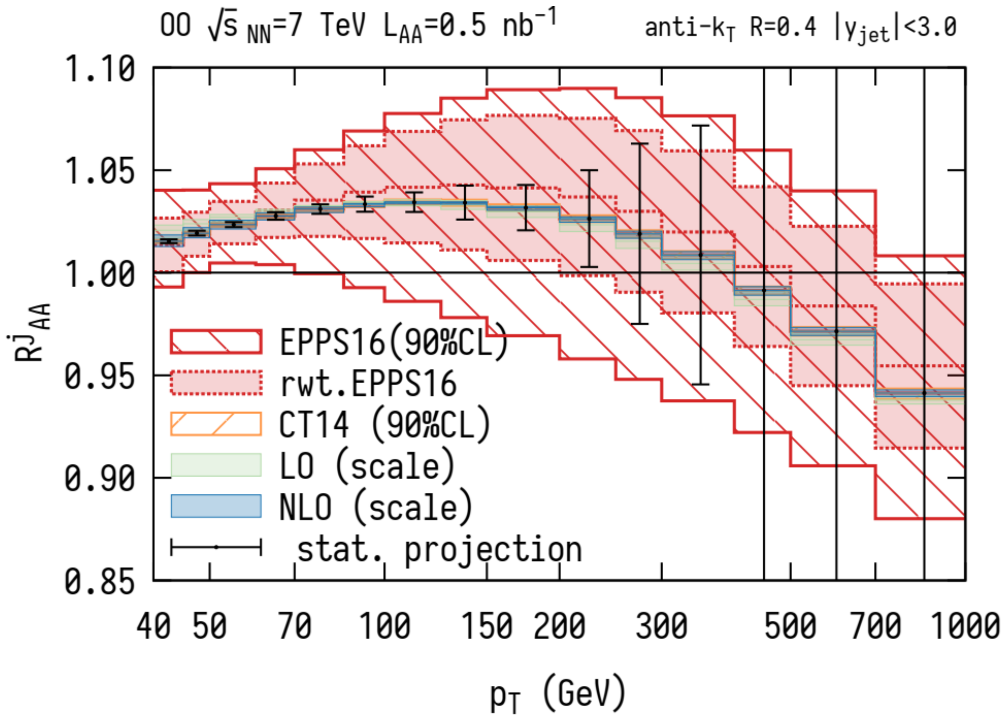
OO collisions as an example:
Nuclear modification factor: hadron R_{AA}
More energy loss than pPb
Interplay from HEP and HIP

A. Huss, A. Kurkela, A. Mazeliauskas, R. Paatelainen, WS and U. Wiedemann, Discovering partonic rescattering in light nucleus collisions (2020)

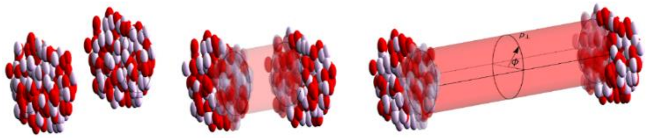
Nuclear effects

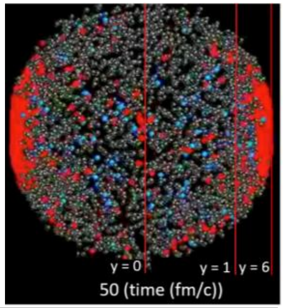
Compare pp jet/hadron production with OO, assuming no plasma

1. Factorisation: PDF + pQCD hard matrix + Fragmentation
   - PDFs: CT14 for pp, EPPS16 for OO
   - pQCD: at NLO (consistent with EPPS) vary renorm and fact scale, errors mostly cancel in ratio
   - Include extra dijet data: reweighting of nPDF set reduces error considerably
   - Expected R_{AA} ~ 5%, error 2 – 5%



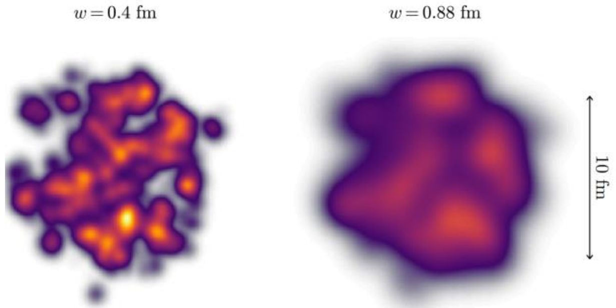
Standard model of heavy ion collisions





Initial stage (9)

Subnucleonic structure? (7)

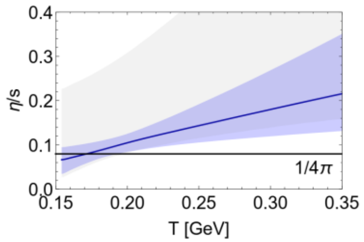


Non-thermal flow? (2)
for time τ with varying speed (***new***)

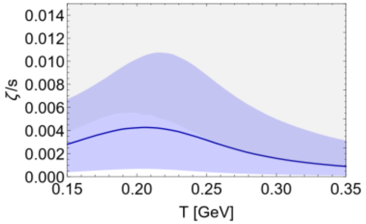
Fluctuations? (1)

Viscous hydrodynamics (9)

Shear viscosity (3)



Bulk viscosity (3)



Second order transports: 3 (***new***)

Cascade of hadrons (1)

Convert quark-gluon plasma at T_{switch} to particles following Boltzmann distribution (particlization, 1)

Subtle: viscous corrections

Evolve particles with hadronic code: SMASH

Jonah Bernhard, Scott Moreland and Steffen Bass, Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma (2019)
Govert Nijs, WS, Umut Gursoy and Raimond Snellings, A Bayesian analysis of Heavy Ion Collisions with Trajectum (2020)

Optimal center-of-mass energy for pO / OO

Maximum energy	**Same $\sqrt{s_{NN}}$ as PbPb / pPb**
7 TeV OO / 9.9 TeV pO	5.52 TeV OO / 8.79 TeV pO
1.5 higher luminosity	2-3 extra days tuning / system
pp reference?	Re-use pp reference from PbPb, pPb

Van der Meer scan: 2 hr/exp (1.5-3% accuracy)

Can pp reference be reliably interpolated? Which observables?

Energy loss in OO?

- Small signal expected: uncertainties of theory baseline (nPDFs) is crucial.
- No oxygen data in nPDF fits. Constraints from dijet R_{FB}, and R_{pO} in pO without reference?
- Experimental projections for hard probes (R_{AA}, high-p_T v_2, h-jet).
- Need for theory developments on integrated soft and hard modelling.

What energy loss signal can be detected (without pp reference) and with which observables (MB / centrality, inclusive, semi-inclusive)?

Quark-gluon plasma in OO?

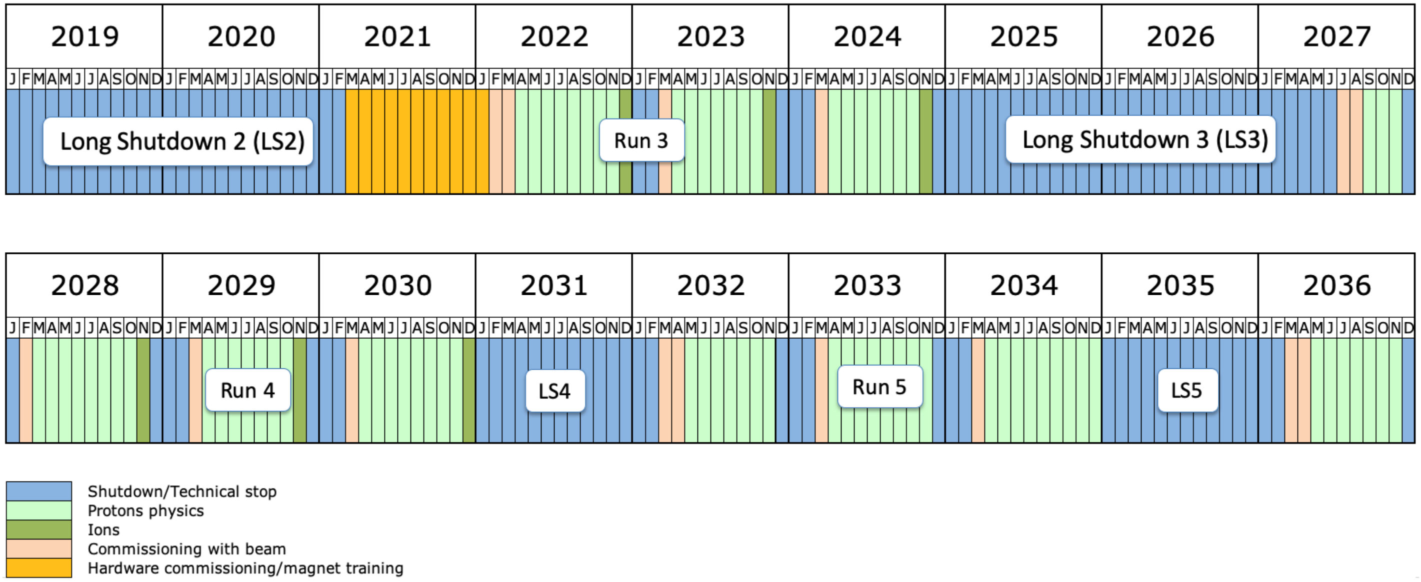
- OO "sweet spot" between pPb and PbPb (but hotter and smaller than PbPb at same multiplicity).
- Extensive hydro model predictions – going beyond?
- Accurate flow measurements (up to $v_2\{12\}$, $N_{ch} < 100$).
- Change of sign in v_2-p_T correlation in peripheral OO?
- Geometry control in OO:
  - Any sensitivity to alpha clustering?
  - Subnucleonic fluctuations (> than PbPb, < pPb).

What can be ruled out with OO data?

pO and cosmic rays

- LHCb and LHCf probe relevant forward regions for cosmic rays and Pierre Auger.
- Significant luminosity for fixed target with various systems in SMOG2 (OO, PbO and many more).
- Unique opportunity window (LHCf can only take data in Run 3).

What impact will pO have on CR shower interpretation?



For reference

Single-Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	Run Time	Species	Events (MinBias)	Priority
3.85	7.7	11-20 weeks	Au+Au	100 M	1
3.85	3 (FXT)	3 days	Au+Au	300 M	2
44.5	9.2 (FXT)	0.5 days	Au+Au	50 M	2
70	11.5 (FXT)	0.5 days	Au+Au	50 M	2
100	13.7 (FXT)	0.5 days	Au+Au	50 M	2
100	200	1 week	O+O	400 M 200 M (central)	3
8.35	17.1	2.5 weeks	Au+Au	250 M	3
3.85	3 (FXT)	3 weeks	Au+Au	2 B	3

E_{beam} / Z	$\sqrt{s_{NN}}$(pp)	$\sqrt{s_{NN}}$(PbPb)	$\sqrt{s_{NN}}$(XeXe)	$\sqrt{s_{NN}}$(OO)	$\sqrt{s_{NN}}$(pPb)	$\sqrt{s_{NN}}$(pO)	Year
2.51	5.02						2015, 2017
2.76	5.52						?
3.19	6.37						?
3.5	7						?
4					5.02		2012, 13,16
5.02				5.02			??
5.52				5.52			??
6.37		5.02		6.37	8.00	9.00	2015,18, Run 3,4?
6.5			5.44		8.16		2017, 2016
7		5.52		7.00	8.79	9.90	Run 3,4?

OLD

Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1}
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	